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(54) A method of measuring the velocity of liquid flow

Verfahren zur Messung der Geschwindigkeit einer Flüssigkeitsströmung

Procédé de mesure de la vitesse d'écoulement d'un liquide

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Description

This invention is concerned with measuring the relative and absolute velocity of liquids, specifically of water or fluids mixed with water, as applied to oil-field operations.

Depleted oil production zones may be rejuvenated by water flooding. In this process the casing opposite the formation under consideration is plugged off by packers above and below the production zone. Water injection tubing, nested within the casing of an injection well, allows injection water to flow down the tubing to the desired injection zone, exit the tubing through specialized hardware, and flow in the annulus between the tubing and the casing. From this annulus the water enters the formation through perforations in the casing, pushing the oil in the formation ahead of the water-flood front. For good and sufficient reasons it is very important to the operator to monitor the velocity of the water flow in the tubing-casing annulus, and therefore the volumetric flow into a particular zone of the formation, throughout the vertical profile of the well.

Various methods are known for measuring the water-flow velocity through a single conduit such as the injection tubing itself. For example, the water flow velocity within the injection tubing can be measured by placing a spinner-type flowmeter inside the tubing. However, that method can not, of course, be used to measure the flow velocity in the annulus between the tubing and the casing which is inaccessible to a mechanical flowmeter.

Methods of measurement, which do not rely upon direct access to the flow stream in the tubing-casing annulus, have been described to measure the velocity of water flowing in the annulus. A radioactive tracer, for example, could be mixed with the injected fluid to monitor the progress of the fluid with detectors sensitive to radioactive decay. That method is unattractive, first because of the need for handling radioactive substances and, second, because the results are highly qualitative.

Another method, referred to as oxygen activation, may be used to measure the velocity of water flow inaccessible to direct measurement. This method consists of continuously irradiating the oxygen nuclei of the flowing water with high-energy neutrons to generate therefrom the unstable isotope N^{16} which has a half life of 7.13 seconds. As the isotope decays, gamma rays are emitted which are counted by two radiation detectors downstream of the source that are spaced a distance, s, apart. The time behaviour of the recorded count rates as seen at the two detectors follow the relation

$$C_1 = K \exp\{-\lambda t1\} \qquad (1)$$

and

$$C_2 = K \exp\{-\lambda t2\} \qquad (2)$$

where C_1 and C_2 are the respective count rates at times t1 and t2, at distances d1 and d2 = (d1+s) from the source where d1 is the distance from the source to the near detector, K is the decay rate at time t1 = t2 = 0, and λ is the N^{16} decay constant. Using these relations and expressing time as the ratio of distance to velocity, the velocity of activated water flowing between the two detectors, V_w, is given by

$$V_w = s\lambda/(\ln(C_1) - \ln(C_2)) \qquad (3)$$

Another method for using oxygen activation to measure the velocity of water, referred to as the impulse method, differs from the above method in that the source is turned on and off, for example in a 10-seconds-on and 60-seconds-off pattern. In this method, a localized volume of water in the region of the source is activated when the source is on and its time of passage past the detector is noted as a peak in the count rate. The velocity of the flow maybe calculated from the time of passage and the known distance from the source to the detector.

While all of the current methods that employ oxygen activation to measure water flow are capable of measuring the velocity of water flow in the tubing-casing annulus, none can do so, for practical purposes, if there is an additional, physically separate, stream of water present flowing in the same direction (a co-directional flow stream) at a different velocity. In that case the neutron source bombards the O^{16} nuclei of both volumes of water at the same time and the detectors cannot distinguish between the counts from the two flow volumes because of superposition of the decay activity. Hence, the measurement of the velocity of water flow in the presence of multiple co-directional flow streams is not possible using the current methods of oxygen activation.

Some of the applicable patents include US Patent No. 3,603,795. This patent teaches a method substantially the same as the method described by equations (1), (2) and (3). That patent also directs its application to the detection of water flow outside the casing as well as inside.

A trilogy of US Patents, No. 4,032,780, No. 4,032,778 and No. 4,035,640, teaches various aspects of measuring water flow in the region outside the well casing where water might flow between stratigraphic levels through channels in the casing-cement-formation annuli. Such channels are the result of an incomplete cement seal between the casing exterior and the borehole wall in the formation. Water flowing in these channels is referred to as "behind casing water flow".

The '780 patent teaches a method to measure the volume flow rate of behind casing water flow by using a measurement of the flow velocity and an estimate of the

distance R to the flow region. The velocity of the undesired water flow is calculated from the count motes in substantially the same manner as described using equations (1), (2) and (3).

The '778 patent teaches a relationship for the count rate ratio of two distinct energy regions of the gamma ray spectrum as a function of the distance from the gamma ray source. The distance to the flow channel is determined using this ratio. The calculation of the flow velocity is made in substantially the same manner as described using equations (1), (2) and (3). Using the measured velocity and distance to the channel, the volumetric flow rate may be determined.

The '640 patent teaches that background radiation due to prompt (n,γ) radiation is largely avoided if the high energy neutron source is quickly pulsed and the measurements of activation count rates are made between the pulses. The linear water flow velocity of the undesired flow is calculated from the count rates in substantially the same manner as described using equations (1), (2) and (3).

In a paper entitled Applications of Oxygen Activation for Injection and Production Profiling in the Kuparuk River Field, published as paper 22130 in May, 1991 by the Society of Petroleum Engineers, H. D. Scott et al. teach use of a stationary logging instrument for measuring fluid velocity by oxygen activation using the impulse method described above. Referring to the interference from codirectional flows, the authors state that "...If flow does exist inside the tubing from zones below the packer, it may be difficult or impossible to quantitatively interpret the data from the zone of interest because of superposition of the flowing signals...." In the application under discussion in the Scott et al. paper, the annular flow velocity to be measured is in the upward direction and the interfering flow is the tubing flow in the upward direction from zones beneath the region of the measurement. Later in the paper, the authors point out that if co-directional water flows having widely different velocities are present (such as 91 cm [3 feet] per minute and 30 m [100 feet] per minute), the two velocities may be individually measured by use of a third, long-spaced, detector for measuring the fast flow.

None of the presently available art solves the need for a general and practical method capable of measuring the velocity of the fluid flow in the annulus between the inner and outer conduit in the presence of co-directional flow in the inner conduit where two separate conduits are nested together. None of the references are directed to a general and practical method for measuring the flow velocity in the tubing-casing annulus where the difference between the flow velocities in the tubing and the annulus is not great.

According to one aspect of the invention there is provided a method for measuring the relative and absolute velocity of a volume of water, or fluids mixed with water, flowing through an annulus between an inner and an outer conduit pair nested in a well bore in the presence of water flowing co-directionally in the inner conduit at the time of the measurement; a cable-suspended logging instrument is passed through the inner conduit, the instrument containing a source of high energy neutrons, two gamma ray detectors spaced a distance s apart, associated signal processing and transmission electronics and a mechanical flowmeter. A mathematical description is formulated for the recorded count rate due to the decay of the activated water flowing in the inner conduit as an analytical function of the relative velocity between the inner conduit flow and the instrument. The mathematical description is formulated for each detector by the principle of velocity gauging. This analytical description of count rate vs. relative inner conduit velocity is defined as the tubing count rate profile.

Having determined the tubing count rate profile, the logging instrument is introduced through the tubing to a zone of interest in the well where the flow velocity of the water volume in the annulus between the nested inner and outer conduits is to be measured. The logging instrument is moved through the tubing in the well bore at a velocity v_c where $O \leq v_c < v_1$ and where v_1 is the annular flow velocity. The O^{16} nuclei of the water molecules are activated by high energy neutrons from the source to produce the unstable isotope N^{16} which decays to produce measurable gamma rays. The detectors measure the total gamma ray count rate. The instantaneous velocity v_2 of the water flow in the tubing relative to the instrument is measured concurrently by the mechanical flowmeter. From the tubing count rate profiles for the detectors, the tubing count rates corresponding to the measured instantaneous relative tubing flow velocity is determined and subtracted from the total gamma ray count rates to yield corrected count rates. The relative fluid velocity V in the annulus is determined from the ratio of the corrected count rates in the two detectors. The absolute velocity V_{abs} of the annular flow is the sum of the cable velocity v_c and the measured relative velocity V.

For a better understanding of the invention and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings, wherein:

FIGURE 1 is a schematic diagram of an inner water-injection conduit, or tubing, nested inside an outer conduit, or casing, in a well bore and showing a cable-suspended logging instrument arranged for vertical movement within the inner conduit;

FIGURE 2 is an enlargement of that portion of FIGURE 1 involving the logging instrument;

FIGURE 3 is a plot of the measured gamma ray count rate as a function of relative water flow velocity for a 5.08 cm (2 inch) diameter channel of water adjacent to the instrument;

FIGURE 4 is a plot of the measured gamma ray count rate as a function of relative water flow velocity for an instrument centred in a 7.30 cm (2.875")

tubing nested in a 17.78 cm (7.0") casing;

FIGURE 5 is a plot of the modeled count rate behaviour as a function of instrument velocity showing the outer conduit (slower velocity flow) and inner conduit (faster velocity flow) contributions and the resulting total count rate resulting from the superposition of the two components; and

FIGURE 6 is a graph of the outer conduit relative velocity as measured using the methods of this disclosure vs. the true outer conduit relative velocity as independently measured by a calibrated flowmeter.

Mechanical Details

Figures 1 and 2 represent a cross section of a portion of an injection well penetrating a subsurface formation 10 to a region associated with an injection zone 12. Casing 14 includes multiple perforations 16 opposite the porous injection zone 12. Injection tubing 18, nested inside casing 14 is provided with openings 19 so that the injection fluid flows under pressure into the annulus 20 between the inner conduit or tubing 18 and outer conduit or casing 14, thence into the formation via the perforations 16 to sweep oil towards a production well (not shown). Packers 13 and 15 confine the injection water in casing 14 to a desired production zone 12. For purposes of this disclosure, the water flow volumes in the annulus and in the tubing are co-directional as shown by the arrows V1 and V2 respectively. The velocity of the logging instrument 22 is symbolized by arrow V_c (velocity of cable).

The logging instrument 22 is a modification of a conventional neutron logging instrument such as the PDK-100 (Atlas Wireline Services registered service mark) provided by the assignee of this invention. It consists of an elongated mandrel 24 of suitable material, 4.23 cm (1.6875") in diameter, supported by a cable 26 that is coupled to the draw works 27 at the surface for deployment through the inner conduit or injection tubing 18. The velocity of the instrument 22 as it is drawn through the conduit 18 is measured by an odometer/velocimeter of any well known type 29 that may be associated with a sheave over which the supporting cable 26 passes.

A pulsed neutron source 28 is mounted inside one end of the instrument 22 and separated from the interiorly-mounted near and far gamma ray detectors 30 and 32 by a shield 34. A third gamma ray detector 36 may be provided. It is to be understood that the detectors may be mounted beneath the source as shown in Figure 1 or above the source. The selection of the configuration depends upon the direction of the water flow to be measured. A mechanical flowmeter 40 is secured to the bottom of the instrument 22 for measuring the velocity of the fluid in the inner conduit relative to the instrument. Signal processing electronic circuitry (not shown) is installed in compartments of the instrument to discriminate against low level gamma ray activity in favor of the higher energy deriving from the activated oxygen. The detector count rates are digitized downhole and are telemetrically transmitted to the surface through suitable conductors in supporting cable 26 to processing and archival storage unit 31 at the surface.

In operation, the neutron source is pulsed at 1 kHz for 28 milliseconds (ms) and is then shut off for 8 ms during which time the count rate measurement is made. The third gamma ray detector 36 may be used in conjunction with either of the detectors 30 or 32 to increase the detector spacing for the measurement. However, it is most often used to identify specific rock boundaries in the well as determined by correlation with a previously-derived well-logging graph of natural gamma radiation.

During a fluid velocity measurement logging run, four quantities are measured. The instrument telemeters the total gamma ray count rates as measured by each of the two detectors 30 and 32 and the relative velocity of the fluid in the inner conduit as measured by the flowmeter 40, to the surface processing equipment 31. The logging instrument cable velocity as measured by the cable velocity odometer 29 is sent to the processing device 31 over a separate channel 33. As will be explained now, from those four inputs, the fluid velocity in the outer conduit, such as the annular space 20, may be calculated.

Mathematical Model

Given the instrument located in the inner conduit and a volume of water or fluid mixed with water flowing in the inner or outer conduits, the ability to mathematically describe the recorded count rates generated by either flow with an analytic function of the relative flow velocity is fundamental to the method described here. To examine such a description, consider the general case of a water stream flowing adjacent to the instrument. The flow stream is activated by the high energy neutrons emanating from the source 18. The resulting gamma rays from the radioactive decay of the N^{16} isotope are detected by the near and far detectors 30 and 32. The decay activity as measured in counts per second is described by

$$CR = (A/v)\exp\{-\lambda B/v\}, \qquad (4)$$

where

v = flow velocity relative to the instrument,

CR = measured count rate corrected for background when necessary and normalized to source output,

λ = N^{16} decay constant,

A, B are adjustable parameters.

Laboratory data for near and far detectors is shown

in Figure 3 where the data were taken with a 5.08 cm (2 inch) diameter flow stream adjacent to the instrument. The curves 42 and 44, of the form of equation (4), have been constructed by optimizing parameters A and B using weighted least squares variance minimization. The resulting curves provide a satisfactory description of the measured data.

Laboratory data were also taken in the configuration where the instrument is contained in the inner conduit of an inner and outer nested pair of concentric conduits. The inner conduit was constructed of 7.3 cm (2.875") diameter, 28.9N (6.5 pound) production tubing and the outer conduit was 17.78 cm (7") diameter production casing. Water could be configured to flow in the inner and outer conduits individually and separately or in both simultaneously. Figure 4 shows the measured count rates for the near and far detectors as a function of the relative velocity between the instrument and the flow. The data shown are for individual, separate flows in the inner and outer conduits. The curves show the optimized fit of equation (4) to the data. Curves 41 and 43 apply to the near detector and curves 45 and 47 apply to the far detector.

Having demonstrated that the behaviour of the count rate as a function of relative flow velocity can be described by equation (4) for flow in both inner and outer conduit flows, consider now the instrument deployed in a conduit where it is in motion co-directionally with the water flow contained in that conduit. If the velocity of the instrument is the cable velocity, v_c, the velocity of the flow in the conduit is v_2, and $v_2 > v_c$, then the velocity of the flow relative to the instrument is

$$v = v_2 - v_c$$

and equation (4) can be expressed as a function of v_c. The shape of the resulting function for v_2 = 6.1 m (20 feet) per minute is shown by the curve 48 in Figure 5 where A = 20 and B = 1 for illustration.

In the operational configuration, an inner conduit containing the instrument is nested within an outer conduit and there are co-directional water flows in both conduits. Since the behaviour of the count rate from the outer flow as a function of relative velocity can be described by a function of the form of equation (4), a model of the count rates from both inner and outer flows as a function of v_c is shown in Figure 5 where the individual contributions originating from both the inner and outer flows are shown separately and superimposed as they would be recorded by the detectors. For the purpose of illustration, the velocity of the outer-conduit flow v_1 is arbitrarily set at 6.1 m (20 feet) per minute, that of the inner flow v_2 is set at 12.2 m (40 feet) per minute, B = 1 for both flow descriptions, and the amplitude of the slower flow is 20% of the faster flow. The dashed curve 46 represents the count rate contribution originating from the inner conduit, the dotted curve 45 represents that from the outer conduit flow, and the solid curve 50 represents the sum of the inner and outer contributions. Over the region from v_1 to v_2 the curves 46 and 50 are co-linear since the total recorded count rate is due only to the inner conduit flow.

For v_c above 0.203 m/s (40 fpm), the instrument outruns the motion of the activated fluid volumes in both the inner and outer conduits so no counts are recorded from the flows. In the range where $v_1 < v_c < v_2$, only counts from the flow in the inner conduit contribute to the total count rate as the instrument is outrunning the slower flow in the outer conduit. In the range where $v_c < v_1 < v_2$, the total count rate receives contributions from the fluids in both conduits.

The essence of this embodiment is a method for correcting the total count rate when operating in the range where $v_c < v_1 < v_2$ in order to isolate the count rate contribution from the outer conduit flow. This method involves characterizing the inner conduit flow count rates by equation (4) prior to logging and subtracting the result from the total count rate measured during the logging run. The method of velocity gauging is used to accomplish this characterization.

The Tubing Count Rate Profile and the Method of Velocity Gauging

The method of velocity gauging as used to analytically characterize the gamma ray count rate from the irradiated fluid flow in the inner conduit consists of, first, a series of constant-cable-velocity measurements gauged to be contained in the cable velocity range $v_1 < v_c < v_2$ where the faster inner conduit flow may be measured without interference. Then equation (4) is fitted to the resulting count rate vs. relative velocity data by weighted least squares variance minimization to optimize the parameters A and B thereby to formulate a mathematical description of the count rates as a function of the relative velocity between the inner conduit flow and the instrument:

$$C1_i = (A1_i/v)\exp\{-\lambda B1_i/v\} \qquad (5)$$

$$C2_i = (A2_i/v)\exp\{-\lambda B2_i/v\} \qquad (6)$$

where

$C1_i$ and $C2_i$ refer to the count rates due to the inner flow in the near and far detectors respectively and v is the relative velocity between the instrument and the inner flow as measured by the mechanical flowmeter. Equations (5) and (6) are defined as the tubing count rate profiles. Having characterized the inner conduit flow in the form of tubing count rate profiles for both the near and far detectors, the profiles are used to predict the count rate originating from the inner conduit at any ar-

bitrary relative velocity as measured by the flowmeter 40 and allow the subtraction of the inner conduit contribution from the total count rate at any arbitrary relative velocity of inner conduit flow and, therefore, the isolation of the count rates originating from the outer conduit from which the velocity of the annular, or outer conduit flow, is determined.

On first examination it may appear that the above argument is circular or contradictory in that the outer conduit velocity, v_1, is employed in the specification of the velocity gauging procedure, whereas the purpose of the measurement is the determination of v_1. The resolution is that there are some regions in each well where the outer conduit velocity is known to be approximately zero and therefore the gauging of the cable velocities for the purpose of characterizing the inner conduit flow in such regions is trivial. Such a region would be above the first fluid exit points in the inner tubing 18 and above any packers, such as 13, Figure 2, which are used to isolate an injection zone. It is also possible, however, to characterize the inner flow in a region where the outer flow is known to be non-zero by determining the greatest upper bound on the outer conduit flow velocity, v_1, based on calculations using the injection rates measured at the surface.

<u>Calculation of the Outer Flow Velocity</u>

Following the characterization of the inner flow and the construction of a tubing count rate profile, stationary and/or continuous measurements may now be made over the region of interest. During these measurements, the flowmeter provides an instantaneous measurement of the velocity of the fast flow in the inner tubing string 18 relative to the instrument. From these measurements, a correction to the total measured count rate in both the near and far detectors 30 and 32 can be made:

$$C1_o = C1_1 - C1_i \tag{7}$$

$$C2_o = C2_1 - C2_i \tag{8}$$

where

the suffixes 1 and 2 denote the near and far detectors, respectively,

$C1_o$ and $C2_o$ are the corrected outer conduit flow count rates,

$C1_1$ and $C2_1$ are the total measured count rates, and

$C1_i$ and $C2_i$ are the inner conduit flow count rates calculated from equations (2) and (3) and the flowmeter measurement of relative velocity.

Since the annular flow in the outer conduit can be characterized in the same functional form as equation (1):

$$C1_o = (D1/V)\exp\{-\lambda E1/V\} \tag{9}$$

$$C2_o = (D2/V)\exp\{-\lambda E2/V\} \tag{10}$$

where

V is the velocity of the outer conduit flow relative to the instrument, and

D1, D2, E1, E2 are laboratory-derived parameters characteristic of the borehole and conduit geometry.

The relative velocity V of the volume of fluid in the outer conduit is determined from the ratio of the corrected count rates:

$$V = \frac{\lambda(E2-E1)}{\ln(\frac{C1_o}{C2_o})-\ln(\frac{D1}{D2})} \tag{11}$$

The absolute velocity V_{abs} of the fluid flow in the outer conduit is given by the sum of the measured relative velocity and the cable velocity

$$V_{abs} = V + V_c \tag{12}$$

To illustrate the validity of this method, a series of laboratory measurements of the outer conduit velocity were made using nested conduits consisting of 7.3 cm (2.875"), 28.9N (6.5 pound) production tubing centralized in 17.78 cm (7.0") casing with simultaneous co-directional flows in both conduits. Prior to the velocity measurements, a tubing count rate profile was constructed in the manner described above resulting in the parameters A1, B1, A2, and B2 describing the inner conduit flow. Similarly, laboratory measurements established the parameters D1, E1, D2, and E2 describing the outer conduit flow. Data were then taken with the inner conduit flow fixed at 33.5 m (110 feet) per minute while the co-directional outer conduit flow velocity was varied. The isolation of the outer conduit count rate and the calculation of the outer conduit flow velocity were made in the manner described above. The result is shown in Figure 6 where the true relative flow velocity in the outer conduit, as measured using a calibrated flowmeter on the test fixture, is plotted against the relative flow velocity as measured using the method described herein. The vertical error bars represent the standard error in the measurement and are based on one standard deviation for equal time measurements.

The results show excellent agreement between the measured value and the true value.

Additionally, it may be observed from Figure 6 that the statistical precision of the measurement increases as the relative flow velocity decreases. The method disclosed here, which employs relative measurements, provides the additional benefit that the precision of the measurement can be increased by increasing the cable speed to reduce the relative velocity between the cable and the outer flow velocity. Further, this relative measurement capability produces the significant economic advantage of the measurement of higher outer conduit flow speeds, in principle limited only by the maximum logging speed attainable by the mechanical logging equipment.

Additionally, since the measurement of the count rates, cable velocity, and relative flow velocity of the inner conduit flow are instantaneous, a valid measurement of the outer conduit velocity may be made by drawing the instrument through the inner conduit at some desired velocity which may be a constant velocity, a variable velocity, or zero velocity (the instrument is stationary). This capability provides the significant economic advantage of allowing a continuous log which allows a more accurate determination of the annular velocity between perforation sets and which has not been previously possible using traditional methods of oxygen activation.

This disclosure has been written with a certain degree of specificity for purposes of illustration but not by way of limitation. For example, the method described herein is applicable also to producing wells where the oil is mixed with water and to any other applications where the measurement of the velocity of water, in the presence of co-directional flows, is desired. Scientists working in the art will conceive of variations in the methods taught herein but which will fall within the scope of this invention as defined in the appended claims.

Claims

1. A method for measuring the absolute velocity of a volume of water, or fluid mixed with water, flowing through the outer conduit (14) of a set of conduits including inner (18) and outer (14) conduits nested together, said velocity being measured by use of an instrument (22) including a source (28) of high energy neutrons, at least two gamma ray detectors (30, 32) spaced a distance apart, associated signal processing and transmission electronics, and a mechanical flowmeter (40), the method comprising the steps of :

   (a) formulating a tubing count rate profile for each said detector;
   (b) drawing said instrument through said inner conduit at a known velocity;
   (c) irradiating the fluid volumes flowing through said inner and outer conduits by high energy neutrons from said neutron source to produce the unstable N^{16} isotope from the oxygen nuclei contained in the water nuclei;
   (d) measuring, at each said detector, the total gamma ray count rates due to the decay of the N^{16} isotope;
   (e) measuring the instantaneous velocity of the fluid flow in the inner conduit relative to the instrument by said mechanical flowmeter;
   (f) defining, from the tubing count rate profile for each said detector, the count rates due to the inner flow corresponding to the measured instantaneous relative velocity between said instrument and the inner conduit flow, and subtracting the so-determined count rates from the measured total gamma ray count rates from each detector to define corrected count rates;
   (g) determining the relative velocity of the volume of water or fluid in the outer conduit from the ratio of the corrected count rates; and
   (h) adding the known velocity of the instrument to the measured relative velocity to obtain absolute velocity.

2. A method as defined by claim 1, wherein step (a) comprises the steps of:

   (i) passing an instrument through said inner conduit at each of a plurality of discreet cable velocities v_c that lie in a range that satisfies the inequality

   $$v_1 < v_c < V_2$$

   where v_1 is the estimated greatest upper bound on the absolute velocity of the flow in the outer conduit and v_2 is the absolute velocity of the water flow in the inner conduit;
   (ii) irradiating the water or fluid volumes flowing through said inner and outer conduits by high energy neutrons from said neutron source to produce the unstable N^{16} isotope;
   (iii) measuring the total gamma ray decay count rate of the N^{16} isotope at each said detector;
   (iv) measuring the velocity of the fluid flow in the inner conduit relative to the instrument by means of the mechanical flowmeter;
   (v) formulating a mathematical description of the measured count rate as an analytical function of the measured relative velocity between the logging instrument and the velocity of the fluid volume flowing through the inner conduit.

3. A method as defined by claim 2, comprising: in the step of formulating a mathematical description, in-

troducing adjustable parameters in the mathematical [(step v)] description of the measured count rates for each said detector; and iteratively optimizing the adjustable parameters by weighted least squares variance minimization.

4. A method as defined by claim 1, 2 or 3, wherein said tubing count rate profile predicts the count rate originating from the inner conduit fluid flow as a function of the relative velocity between the logging instrument and the inner conduit fluid flow.

5. A method as defined by claim 1, 2, 3 or 4 wherein said instrument is passed through said inner conduit co-directionally with the fluid flow therein.

6. A method as defined by claim 5, wherein the fluid flows within said nested conduits are co-directional.

7. A method as defined by any one of the preceding claims comprising reducing the statistical uncertainty in the calculated relative outer conduit flow velocity by reducing the relative velocity between the instrument and the fluid flow in the outer conduit.

8. A method as defined by any one of the preceding claims wherein step (g), is defined by

$$V = \frac{\lambda(E2-E1)}{\ln(\frac{C1_0}{C2_0}) - \ln(\frac{D1}{D2})}$$

where

$C1_0$ and $C2_0$ = the corrected count rates,
λ = decay rate,
D1, D2, E1, E2 are laboratory-derived constants,
V is the fluid velocity in the outer conduit relative to the instrument.

9. A method as defined by any one of the preceding claims wherein said instrument velocity is a constant velocity.

10. A method as defined by any one of claims 1 to 8, wherein said instrument velocity is a variable velocity.

11. A method as defined by any one of claims 1 to 8, wherein said instrument velocity is zero.

12. A method as defined by any one of the preceding claims when carried out with the conduits nested in a well bore and with the instrument being a logging instrument suspended by cable in the bore.

Patentansprüche

1. Verfahren zum Messen der Absolutgeschwindigkeit einer Wassermenge oder eines Fluid-Wasser-Gemisches, das durch die äußere Leitung (14) eines Rohrleitungssatzes fließt, bei dem innere (18) und äußere (14) Leitungen ineinander verschachtelt sind, wobei die Geschwindigkeit durch den Gebrauch eines Instruments (22) gemessen wird, das eine Quelle (28) hochenergetischer Neutronen enthält sowie mindestens zwei Gammastrahldetektoren (30, 32), die einen Abstand zueinander haben, zugehörige Signalverarbeitungs- und Übertragungselektronik und einen mechanischen Durchflußmesser (40), und das Verfahren die Schritte umfaßt:

a) Formulieren eines Steigrohr-Zählratenprofils für jeden der Detektoren;
b) Ziehen des Instruments durch die innere Leitung mit einer bekannten Geschwindigkeit;
c) Bestrahlen der Fluidmengen, die durch die inneren und äußeren Leitungen fließen, mit hochenergetischen Neutronen aus der Neutronenquelle, damit aus den in den Wasserkernen enthaltenen Sauerstoffkernen instabile N^{16}-Isotope erzeugt werden;
d) Messen der gesamten Gammastrahl-Zählraten, die durch den Zerfall der N^{16}-Isotope entstehen, mit jedem der Detektoren;
e) Messen der Momentangeschwindigkeit der Fluidströmung in der inneren Leitung relativ zum Instrument mit dem mechanischen Durchflußmesser;
f) Bestimmen - und zwar aus dem Steigrohr-Zählratenprofil für jeden der Detektoren - der Zählraten aufgrund der inneren Strömung, die der gemessenen relativen Momentangeschwindigkeit zwischen dem Instrument und der Strömung in der inneren Leitung entspricht, und Subtrahieren der auf diese Weise bestimmten Zählraten von den gemessenen gesamten Gammastrahl-Zählraten aus jedem Detektor, um korrigierte Zählraten zu bestimmen;
g) Erfassen der Relativgeschwindigkeit der Wasser- oder Fluidmengen in der äußeren Leitung aus dem Verhältnis der korrigierten Zählraten; und
h) Addieren der bekannten Geschwindigkeit des Instruments zur gemessenen Relativgeschwindigkeit, damit man die Absolutgeschwindigkeit erhält.

2. Verfahren nach Anspruch 1, wobei der Schritt a) die Schritte umfaßt:

i) Durchführen eines Instruments durch die in-

nere Leitung jeweils mit einer Anzahl unterschiedlicher Kabelgeschwindigkeiten v_c, die in einem Bereich liegen, der die Ungleichung

$$v_1 < v_c < v_2$$

erfüllt, wobei v_1 die geschätzte größte obere Schranke der Absolutgeschwindigkeit der Strömung in der äußeren Leitung ist, und v_2 die Absolutgeschwindigkeit der Wasserströmung in der inneren Leitung;

ii) Bestrahlen der Wasser- oder Fluidmengen, die durch die inneren und äußeren Leitungen fließen, mit hochenergetischen Neutronen aus der Neutronenquelle, damit instabile N^{16}-Isotope erzeugt werden;

iii) Messen der gesamten Gammastrahl-Zerfallszählrate der N^{16}-Isotope mit jedem Detektor;

iv) Messen der Geschwindigkeit der Fluidströmung in der inneren Leitung relativ zum Instrument mit Hilfe des mechanischen Durchflußmessers;

v) Formulieren einer mathematischen Beschreibung der gemessenen Zählrate als analytische Funktion der gemessenen Relativgeschwindigkeit zwischen dem Meßinstrument und der Geschwindigkeit der Fluidmenge, die durch die innere Leitung fließt.

3. Verfahren nach Anspruch 2, umfassend:

- im Schritt des Formulierens einer mathematischen Beschreibung - das Einführen einstellbarer Parameter in die mathematische Beschreibung [(Schritt v)] der gemessenen Zählraten für jeden Detektor; und iteratives Optimieren der einstellbaren Parameter mit einer gewichteten Fehlerquadrat-Abweichungsminimierung.

4. Verfahren nach Anspruch 1, 2 oder 3, wobei das Steigrohr-Zählratenprofil die Zählrate vorhersagt, die durch die Fluidströmung in der inneren Leitung entsteht, und zwar als Funktion der Relativgeschwindigkeit zwischen dem Meßinstrument und der Fluidströmung in der inneren Leitung.

5. Verfahren nach Anspruch 1, 2, 3 oder 4, wobei das Instrument in der gleichen Richtung wie die Fluidströmung in der inneren Leitung durch die innere Leitung geführt wird.

6. Verfahren nach Anspruch 5, wobei die Fluidströmungen innerhalb der verschachtelten Leitungen gleich gerichtet sind.

7. Verfahren nach irgendeinem der vorhergehenden Ansprüche, umfassend das Verringem der statistischen Unsicherheit in der berechneten relativen Strömungsgeschwindigkeit in der äußeren Leitung durch das Vermindern der Relativgeschwindigkeit zwischen dem Instrument und der Fluidströmung in der äußeren Leitung.

8. Verfahren nach irgendeinem der vorhergehenden Ansprüche, wobei der Schritt g) bestimmt ist durch

$$V = \frac{\lambda(E2 - E1)}{\ln(\frac{C1_0}{C2_0}) - \ln(\frac{D1}{D2})}$$

wobei gilt:

$C1_0$ und $C2_0$ = korrigierte Zählraten,
λ = Zerfallsrate,
D1, D2, E1 und E2 sind Konstanten, die im Labor bestimmt werden,
V ist die Fluidgeschwindigkeit in der äußeren Leitung relativ zum Instrument.

9. Verfahren nach irgendeinem der vorhergehenden Ansprüche, wobei die Instrumentengeschwindigkeit eine konstante Geschwindigkeit ist.

10. Verfahren nach irgendeinem der Ansprüche 1 bis 8, wobei die Instrumentengeschwindigkeit eine veränderliche Geschwindigkeit ist.

11. Verfahren nach irgendeinem der Ansprüche 1 bis 8, wobei die Instrumentengeschwindigkeit null ist.

12. Verfahren nach irgendeinem der vorhergehenden Ansprüche, das ausgeführt wird, wobei die Leitungen in einem Bohrloch verschachtelt sind, und wobei das Instrument ein Meßinstrument ist, das an einem Kabel im Bohrloch hängt.

Revendications

1. Un procédé pour mesurer la vitesse absolue d'un volume d'eau ou d'un fluide mélangé avec de l'eau s'écoulant au travers du conduit extérieur (14) d'un groupe de conduits comprenant des conduits intérieur (18) et extérieur (14) emboîtés conjointement, ladite vitesse étant mesurée par l'utilisation d'un instrument (22) comprenant une source (28) de neutrons à énergie élevée, au moins deux détecteurs de rayons gamma (30, 32) espacés d'une certaine distance, des dispositifs électroniques de transmission et de traitement de signaux associés et un débitmètre mécanique (40), le procédé comprenant les étapes consistant à :

(a) formuler un profil de taux de comptage de tubage pour chacun desdits détecteurs ;
(b) tirer ledit instrument au travers dudit conduit intérieur à une vitesse connue ;
(c) irradier les volumes de fluide s'écoulant au travers desdits conduits intérieur et extérieur par des neutrons d'énergie élevée à partir de ladite source de neutrons pour produire l'isotope N^{16} instable à partir des noyaux d'oxygène contenus dans les noyaux d'eau ;
(d) mesurer à chacun desdits détecteurs, les taux de comptage de rayons gamma totaux dus à la décroissance de l'isotope N^{16} ;
(e) mesurer la vitesse instantanée de l'écoulement de fluide dans le conduit intérieur par rappoit à l'instrument par ledit débitmètre mécanique ;
(f) définir à partir du profil de taux de comptage de tubage pour chacun desdits détecteurs, les taux de comptage dus à l'écoulement intérieur correspondant à la vitesse relative instantanée mesurée entre ledit instrument et l'écoulement de conduit intérieur et soustraire les taux de comptage ainsi déterminés des taux de comptage de rayons gamma totaux mesurés à partir de chaque détecteur pour définir les taux de comptage corrigés ; et
(g) déterminer la vitesse relative du volume d'eau ou de fluide dans le conduit extérieur à partir du rapport des taux de comptage corrigés ; et
(h) ajouter la vitesse connue de l'instrument à la vitesse relative mesurée pour obtenir la vitesse absolue.

2. Un procédé selon la revendication 1, dans lequel l'étape (a) comprend les étapes consistant à :

(i) faire passer un instrument au travers dudit conduit intérieur à chacune d'une pluralité de vitesses de câble discrètes V_c qui s'étendent dans une gamme qui satisfait l'inégalité :

$$v_1 < v_c < v_2$$

où v_1 est la plus grande limite supérieure estimée sur la vitesse absolue de l'écoulement dans le conduit extérieur et v_2 est la vitesse absolue de l'écoulement d'eau dans le conduit intérieur ;
(ii) irradier les volumes d'eau ou de fluide s'écoulant au travers desdits conduits intérieur et extérieur par des neutrons à énergie élevée à partir de ladite source de neutrons pour produire l'isotope N^{16} instable ;
(iii) mesurer le taux de comptage de décroissance de rayons gamma total de l'isotope N^{16} à chacun desdits détecteurs ;
(iv) mesurer la vitesse de l'écoulement de fluide dans le conduit intérieur par rapport à l'instrument au moyen du débitmètre mécanique ;
(v) formuler une description mathématique du taux de comptage mesuré comme une fonction analytique de la vitesse relative mesurée entre l'instrument de diagraphie et la vitesse de l'écoulement de volume de fluide au travers du conduit intérieur.

3. Un procédé selon la revendication 2, comprenant dans l'étape de formulation d'une description mathématique, l'introduction de paramètres réglables dans la description mathématique [(étape v)] des taux de comptage mesurés pour chacun desdits détecteurs et l'optimisation itérative des paramètres réglables par la minimisation de variance des moindres carrés établie.

4. Un procédé selon l'une des revendications 1, 2 ou 3 dans lequel ledit profil de taux de comptage de tubage prédit le taux de comptage provenant de l'écoulement de fluide de conduit intérieur en fonction de la vitesse relative entre l'instrument de diagraphie et l'écoulement de fluide de conduit intérieur.

5. Un procédé selon l'une des revendications 1, 2, 3 ou 4 dans lequel ledit instrument passe au travers dudit conduit intérieur de façon co-directionnelle avec l'écoulement de fluide à l'intérieur de celui-ci.

6. Un procédé selon la revendication 5, dans lequel les écoulements de fluide dans lesdits conduits emboités sont co-directionnels.

7. Un procédé selon l'une quelconque des revendications précédentes comprenant la réduction de l'incertitude statistique dans la vitesse d'écoulement du conduit extérieur relative calculée en réduisant la vitesse relative entre l'instrument et l'écoulement de fluide dans le conduit extérieur.

8. Un procédé selon l'une quelconque des revendications précédentes, dans lequel l'étape (g) est définie par :

$$V = \frac{\lambda(E2-E1)}{\ln(\frac{C1_o}{C2_o})-\ln(\frac{D1}{D2})}$$

où

$C1_o$ et $C2_o$ = les taux de comptage corrigés
λ = taux de décroissance
D1, D2, E1, E2 sont des constantes dérivées

du laboratoire,
V est la vitesse de fluide dans le conduit extérieur par rapport à l'instrument.

9. Un procédé selon l'une quelconque des revendications précédentes, dans lequel ladite vitesse de l'instrument est une vitesse constante.

10. Un procédé selon l'une quelconque des revendications 1 à 8, dans lequel ladite vitesse de l'instrument est une vitesse variable.

11. Un procédé selon l'une quelconque des revendications 1 à 8, dans lequel ladite vitesse de l'instrument est zéro.

12. Un procédé selon l'une quelconque des revendications précédentes, qui est mis en oeuvre avec les conduits logés dans un puits de forage et avec l'instrument qui est un instrument de diagraphie suspendu par un câble dans le puits de forage.

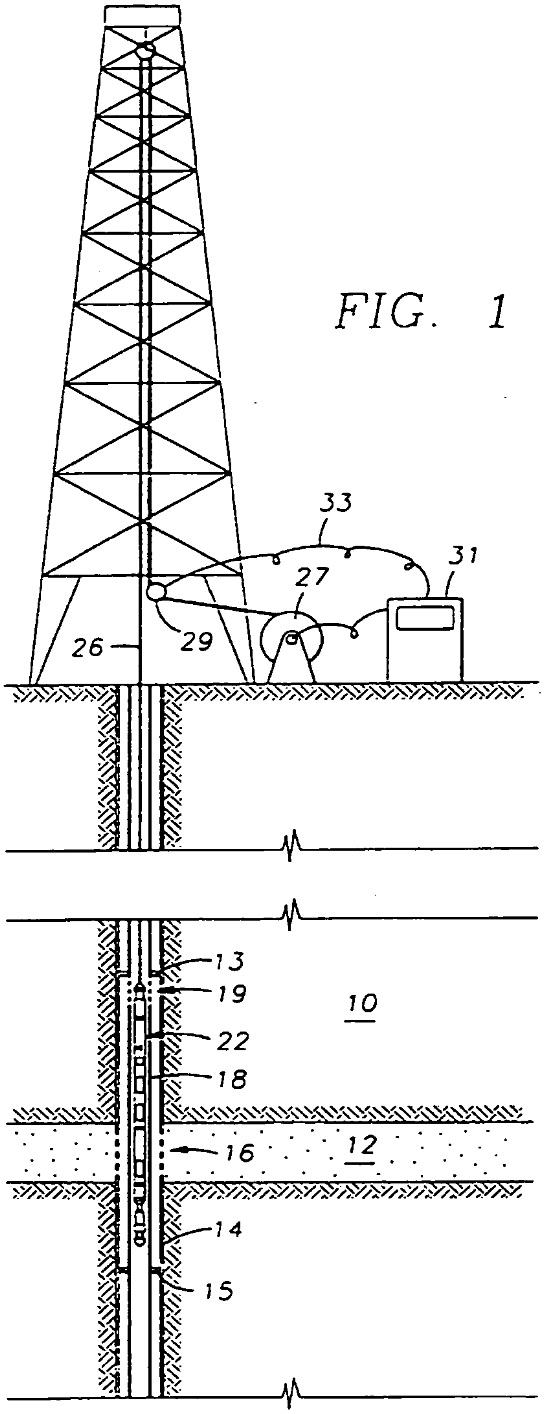
FIG. 1
33
31
27
26
29
13
19
10
22
18
16
12
14
15

FIG. 1

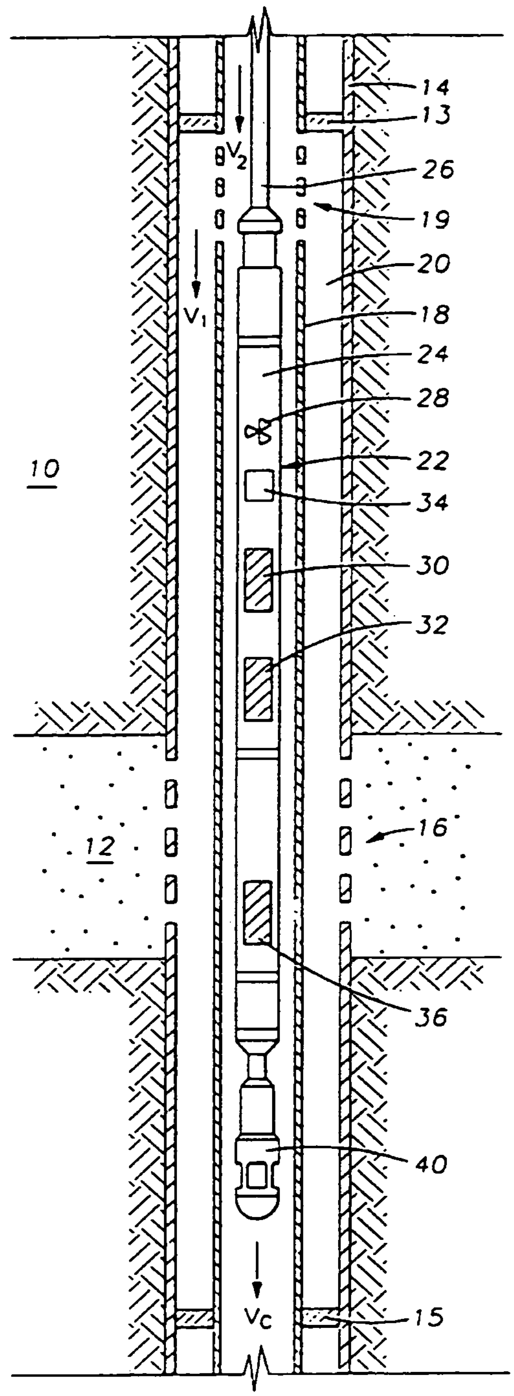
14
13
V_2
26
19
20
V_1
18
24
28
22
10
34
30
32
12
16
36
40
V_c
15

FIG. 2

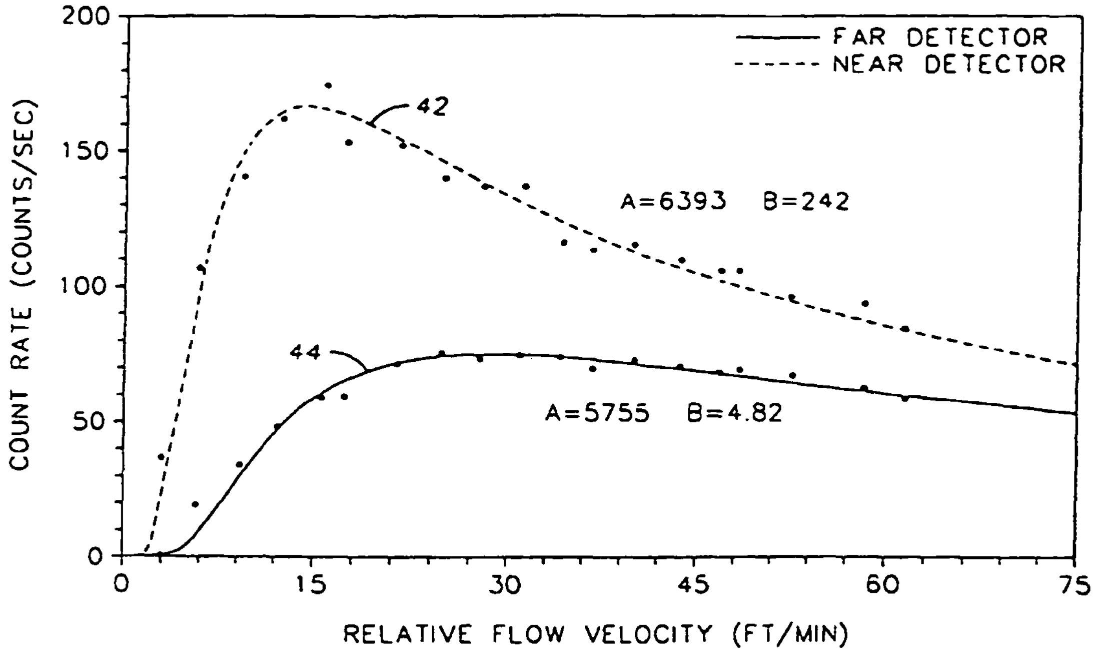
200
150
100
50
0
COUNT RATE (COUNTS/SEC)
0
15
30
45
60
75
RELATIVE FLOW VELOCITY (FT/MIN)
FAR DETECTOR
NEAR DETECTOR
42
44
A=6393 B=242
A=5755 B=4.82

FIG. 3

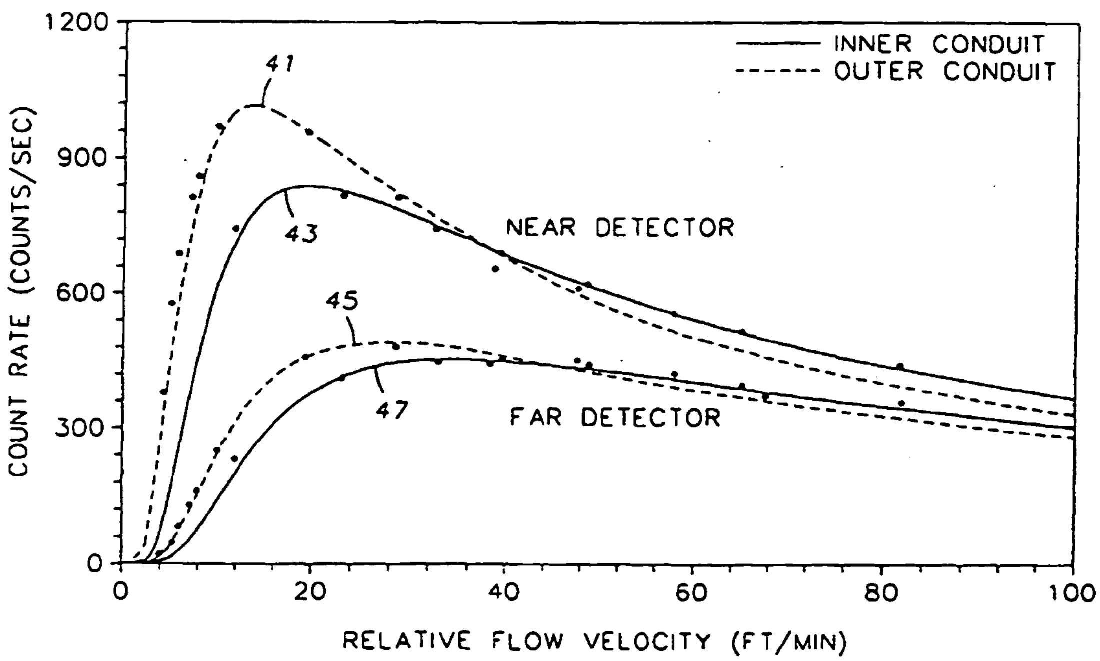
1200
900
600
300
0
COUNT RATE (COUNTS/SEC)
0
20
40
60
80
100
RELATIVE FLOW VELOCITY (FT/MIN)
INNER CONDUIT
OUTER CONDUIT
41
43
45
47
NEAR DETECTOR
FAR DETECTOR

FIG. 4

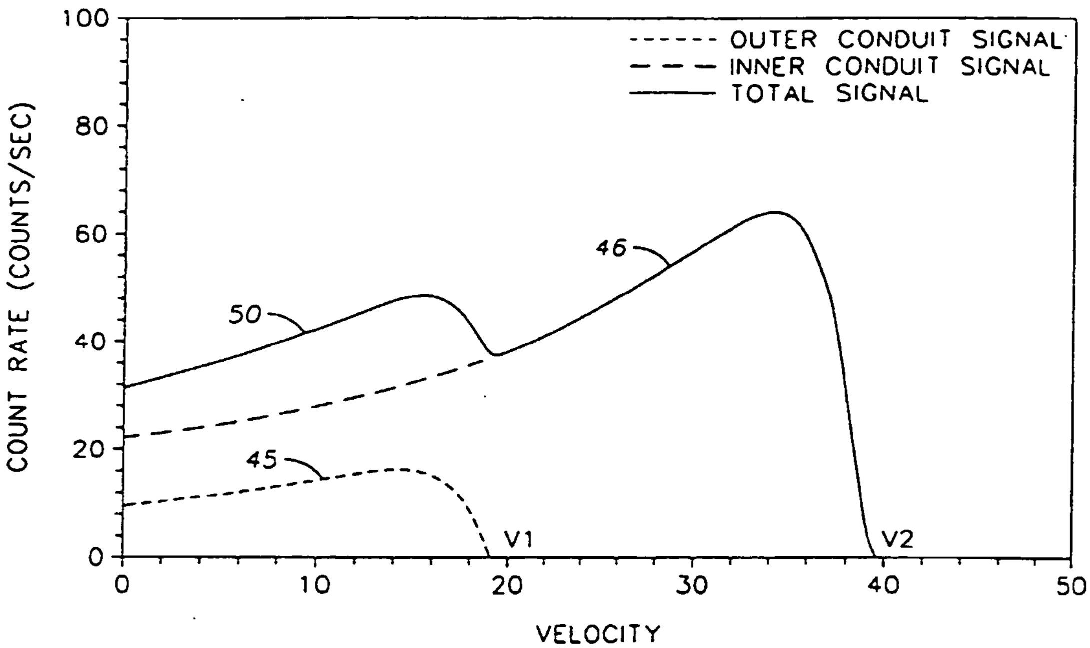
OUTER CONDUIT SIGNAL
INNER CONDUIT SIGNAL
TOTAL SIGNAL
COUNT RATE (COUNTS/SEC)
VELOCITY
50
46
45
V1
V2
0
20
40
60
80
100
10
30
50

FIG. 5

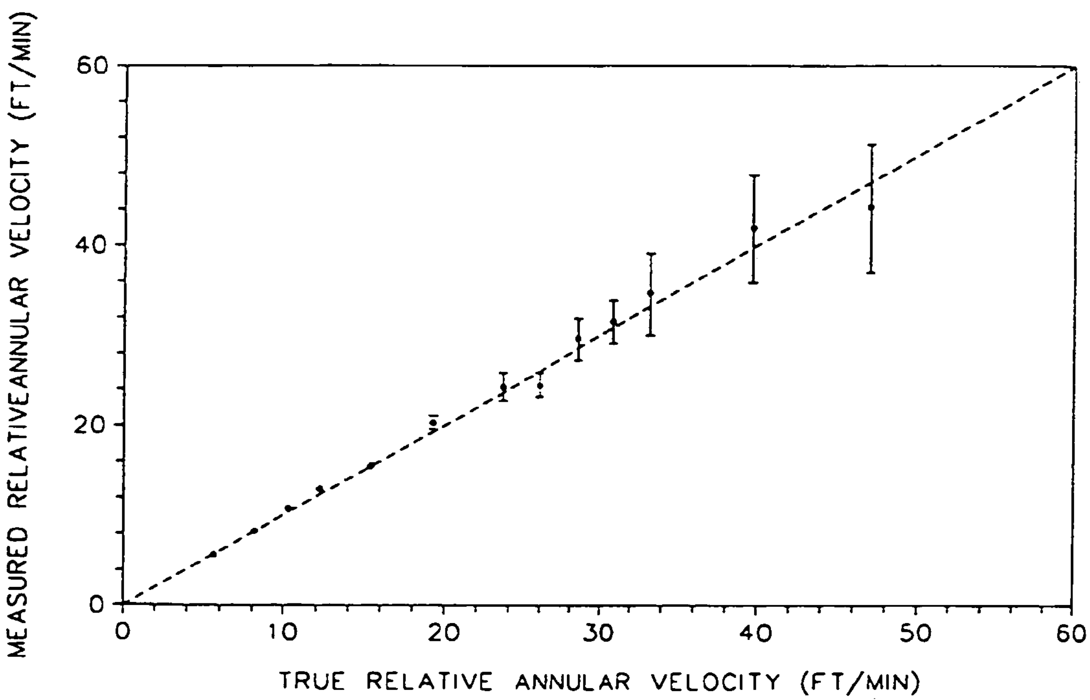
MEASURED RELATIVEANNULAR VELOCITY (FT/MIN)
TRUE RELATIVE ANNULAR VELOCITY (FT/MIN)
0
20
40
60
10
30
50

FIG. 6